ISSN 2250-3153

Growth and Yield Models for Thinned Teak Stands in Taungoo District, Bago Region of Myanmar

Yan Myo Naing

Laboratory of Forest Utilization, Graduate School of Agriculture, Kyoto University, Kitashirakawa Oiwake-cho, Sakyo-ku, Kyoto 606-8502, Japan

DOI: 10.29322/IJSRP.10.05.2020.p10163
http://dx.doi.org/10.29322/IJSRP.10.05.2020.p10163

Abstract- Growth and yield models were developed in this study, especially for teak plantations in Taungoo District, Bago Region of Myanmar. The resultant growth and yield models predict current volume (cubic meter per hectare), instantaneous volume growth rate (cubic meter per year per hectare), instantaneous basal area growth rate (square meter per year per hectare), future basal area (square meter per hectare), and future volume (cubic meter per hectare). These models can be applied in long-term management planning and decision making for teak stands by any desired combination of initial density, site index, thinning regime, and rotation age. Moreover, the results from growth models can be utilized in yield regulation formulae as input.

Index Terms- Teak stands, Growth and yield models, Decision making, Yield regulation formulae, Myanmar

I. Introduction

Teak (*Tectona grandis* L. f.) is one of the most important tropical timber species and is suitable for multiple end-uses. The potential for growing and managing teak in different ecological zones and under different situations is being increasingly recognized, leading to intensive domestication and cultivation of the species in countries/regions beyond its natural habitat [1].

Between 2005 and 2014, the global annual trade of teak roundwood was more than one million cubic meters on average; the imports were valued at US $ 487 million per year, which is about 3 per cent of the value of the global timber trade (US $ 15.5 billion) [2].

Forest Department (FD) of Myanmar has launched a Special Teak Plantation Program since 1998 to maintain and increase teak production. It is designed to annually establish about 8100 hectares of new plantations. Moreover, FD has encouraged the private sector to establish teak plantations at a large scale since 2005. Until March 2010, 13,127 ha of private teak plantations have been established. Across the country, total area of plantations is 967,477 ha, among which that of pure teak is 424,743 ha (43.9 percent of total planted area) [3].

These plantations have been established for commercial purpose under sustained yield basis. In order to achieve this objective, careful and continuous monitoring of the teak crop is essential. However, in Myanmar, scientific research related to reliable growth and yield prediction for thinned teak plantations in a specific area is rare, although it undoubtedly plays a significant role in effective long-term planning and decision making. Therefore, this study was focused on the development of growth and yield models for thinned teak stands in the Taungoo District, which is the eastern part of Bago Yoma Range.

II. MATERIALS AND METHODS

a. Study Site

The teak plantations for the present study (ten stands) are located in Yedashe, Taungoo, Oaktwin and Phyu Townships, Taungoo District, Bago Region, Myanmar. Fig. 1 shows the location of the study site.

b. Methods

Data Collection

Data collection was carried out in 2016. There were ten teak plantations for this study. Each plantation for measurement was selected by the simple random sampling in order to obtain unbiased volume estimation.

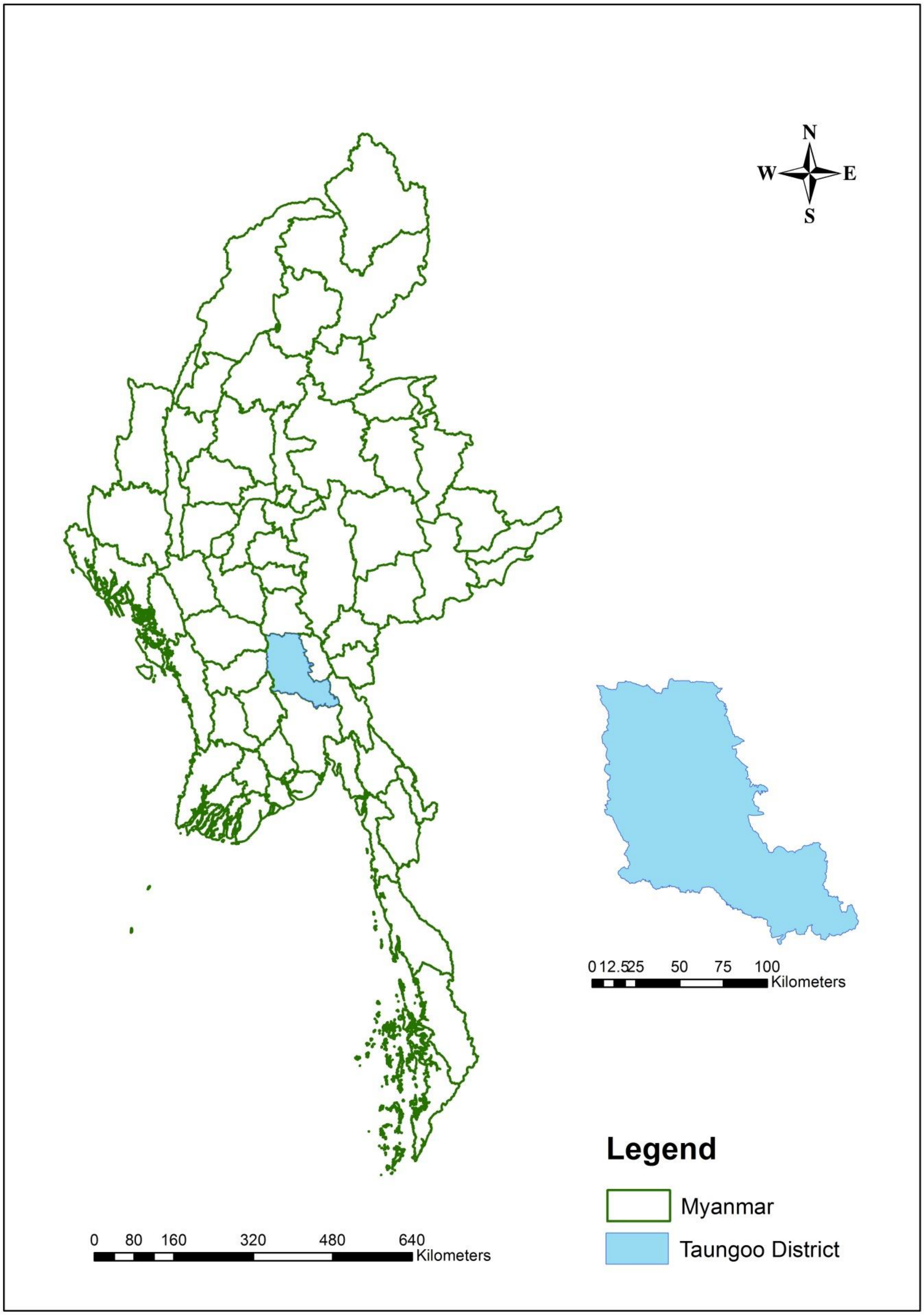


Fig.1. Location of the study site

Sampling frame (a list of the items or people forming a population from which a sample is taken), breast height age, area, thinning frequency, and number of sample plots measured for each plantation were shown in table 1.

Table 1. Age, sampling frame, number of sample plots, area, and thinning frequency

Plantation Number	Age at Breast Height (Year)	Total Number of Sample Plots (Sampling Frame)	Number of Sample Plots Examined	Total Area of Sample plots (ha)	Number of Thinnings Conducted (Times)
1	17	379	10	19	3
2	15	180	10	9	2
3	33	187	10	9	3
4	13	174	10	9	2
5	22	533	10	27	3
6	52	104	10	5.3	4
7	42	70	10	3.5	4
8	40	140	10	7	4
9	46	252	10	12.5	4
10	25	586	10	25	3

Spacing is 2.6 m x 2.6 m for all plantations.
Sample size of volume estimation was calculated by using the following equation [4].

$$n = \left(\frac{ts}{E}\right)^2 \quad (1)$$

where, n is number of sample plots estimated; t is value for student t distribution (for 95% confidence interval, t=2); s is standard deviation of estimated stand volume; E is the desired half width of confidence interval of estimated stand volume also.

In order to estimate the standard deviation, three sample plots of 20m x 25 m (0.05 ha) from plantation (1) were randomly selected. In each sample plot, diameter at breast height (cm) and total height (m) of each tree were measured. Volume for each tree was calculated by the following volume equation developed by [5].

$$V = -\ 0.0230361338 + 0.0000485831D^2H - 0.0000008400D^2H^2 \quad (2)$$

where, V is volume in cubic meters (over bark) up to top diameter of approximately 10 cm excluding stump; D is diameter at breast height in centimeters over bark; and H is total height in meters. In this volume equation, all the parameters and F-test were highly significant ($0.01 < p$). R- square was 0.94.

Total volume of each sample plot, and mean volume and standard deviation of three selected plots were shown in table 2. These plots were measured initially to estimate stand volume which came from plantation number one.

Table 2. Total volume of each sample plot, mean volume and standard deviation (s)

Plot	Volume(m^3)/0.05 ha	Mean Volume (m^3)	Standard Deviation (m^3)
1	14.1		
2	17.2	16.6	2.3
3	18.5		

By substituting the data (t =2; s = 2.3 and E= $\pm$1.5 m^3/0.05 ha) in (Equation (1)), number of sample plots to be collected were derived ($n = [(2^2)\ (2.3^2)]/\ (1.5^2) = 9.2$ plots per plantation).

Therefore, 10 sample plots per plantation were used for sampling thereafter.

Tree-ring Width and Stand Age Estimation

In each plantation, one tree was selected haphazardly in each category of six DBH classes and cored at breast height by using an increment borer. Two core samples from opposite sides of each tree were taken to investigate radial increment. Tree-ring width was measured to the nearest 0.001 mm under a binocular microscope with a linear stage interfaced with a PC computer. MeasureJ2x software was used to measure the tree-ring width. Radial increment was related to age for growth and yield modeling using the regression analysis and simulation technique. Distance between a tree-ring and pith (Fig. 2) was calculated by using the following formula (Equation 3).

$$dA = \sqrt{d^2 + dM^2} \quad (3)$$

where, dA is distance between the pith and a tree ring; dM is the measured distance between tree rings; and d is distance from pith perpendicular to dM (d was read from plastic film).

After calculation of the distance (dA) for each age, the average value from two sample cores for each age was obtained and then to get diameter for specified age, the distance (dA) was multiplied by 2 to convert the variable to stem diameter.

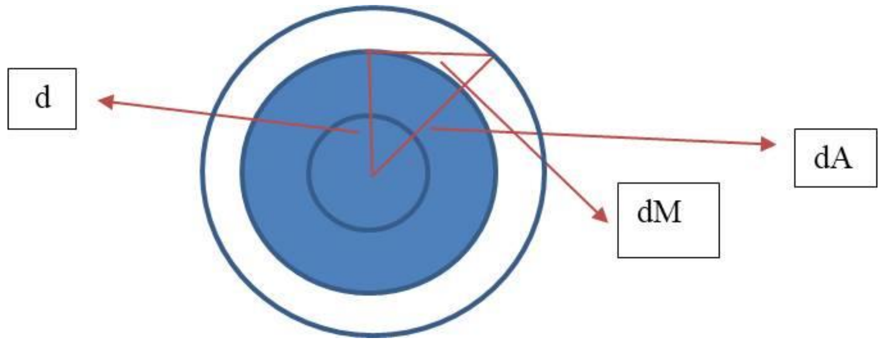


Fig. 2. Distances for calculating a tree-ring width

Measurement in Each Sample Plot

In each sample plot, diameter at breast height (DBH in cm) of each living tree and total height (m) of five biggest trees (DBH) in the sample plot were measured. Total height was measured by Vertex IV hypsometer. In addition, in order to calculate sectional volume, stem diameter at two-meter interval along the stem of each tree was measured by using the Spiegel-Relaskop up to the approximately 10 cm top diameter. Sectional volume was calculated by Smalian`s Formula (Equation (4)).

$$V_s = \pi l(d_L^2 + d_U^2)/8 \quad (4)$$

where, V_s is the volume of a section of a stem; l is the length of the section; d_L is the stem diameter at the lower end of the section (large end diameter) and d_U is the stem diameter at the upper end of the section (small end diameter).

To get total volume up to the 10cm top diameter (excluding stump) for each tree, all the sectional volumes were added. Summation of volume of all living trees gave the total stem volume for the sample plot (0.05 ha). The value was also converted to per hectare basis.

By using top height of each plantation, site index for each plot was derived. The following site index equation developed by [6] was applied in this study.

$$log_{10}S = \left[logH - 1.92038 + 1.92038\left(\frac{A_b}{A}\right)^{0.52514}\right] / \left(\frac{A_b}{A}\right)^{0.52514} \quad (5)$$

where, H is top height (the mean height of 100 largest diameter trees per hectare); S is site index in meter; A_b is base age or index age (80 years in this study); and A is stand age.

Basal area (B) for each tree was calculated by the following formula.

$$B = \frac{\pi DBH^2}{4(10000)} = 0.00007854DBH^2 \quad (6)$$

where, B is basal area in square meters and DBH is diameter at breast height in centimeters.

Plot basal area was the sum of basal area of all the trees in the plot and dividing this sum by 0.05, corresponding to the per-hectare basal area. Basic stand statistics of those used for the analysis were shown in table 3.

Table 3. Basic stand statistics

	Volume (m^3ha^{-1})	Site Index (m)	Breast Height Age (yr)	Basal Area (m^2 ha^{-1})
No. of Observations	100	100	10	100
Minimum	18.3	33.2	13	3.8
Maximum	601.8	46.5	52	73.6
Mean	198.5	40.9	30.5	27.3
Standard Deviation	151.1	2.7	14	17.9

Development of Growth and Yield Models

Whole-stand growth and yield models predict future yields as a function of stand level attributes, such as site index (S), age, and stand density.[7,8,9] developed the earliest whole-stand growth and yield models. [10,11] used a Schumacher yield function as the basis for their compatible growth and yield model for loblolly pine stands. [12]Buckman (1972) also developed a compatible growth and yield model for red pine stands in the Lake States of the U.S.A. In a compatible growth and yield model, the yield function can be found by mathematically integrating the growth function. Subsequently, others used this concept to develop whole-stand growth and yield models for loblolly [13,14,15,16,17,18,19,20] and slash[21,22] pine plantations.

In this study, Schumacher yield function was applied as follow [23].

$$\ln(V) = \beta_0 + \beta_1 S + \beta_2 A^{-1} + \beta_3 \ln(B) \quad (7)$$

where ln is natural logarithm; V is per hectare volume in cubic meter over bark (excluding stump and the tree top approximately above the stem 10 cm diameter); S is site index in meters; A is stand age in year; B is basal area in square meters per hectare; and β_0, β_1, β_2 and β_3 are parameters to be estimated.

[10] listed the desirable features of the above yield model (Equation (7)) as

1. Mathematical form of the variates implies relationships which agree with our biological concepts of even-aged stand development by.[9].
2. Use of ln V as the dependent variable rather than V will generally be more compatible with the statistical assumptions customarily made in regression analysis (linearity, normality, additivity, and homogeneity of variance).
3. Use of ln V as the dependent variate is a convenient way to express mathematically the interaction of the independent variables in their effect on V. (For example, the change in expected volume occurring as a result of a change in site index from 18 m to 21 m would depend on the associated values of ln B and A^{-1}.)

Differentiation of the above (Equation (7)) with respect to age gave the following equation.

$$\frac{dV/dA}{V} = -\beta_2 A^{-2} + \beta_3 \left(\frac{dB/dA}{B}\right)$$

And then

$$\frac{dV}{dA} = -\beta_2 V A^{-2} + \beta_3 V \left(\frac{dB/dA}{B}\right) \quad (8)$$

where $\frac{dV}{dA}$ is the relative rate of volume growth or instantaneous volume growth rate (growth at age A).

In order to obtain an estimate of basal area growth, [23] suggested the following equation forms.

$$\ln(B) = \alpha_0 + \alpha_1 S + \alpha_2 A^{-1} + \alpha_3 ln(B_{20}) A^{-1} + \alpha_4 A^{-1} S \quad (9)$$

where, α_0, α_1, α_2, α_3, and α_4 are parameters to be estimated and B_{20} = basal area at age 20.
Differentiation of the (Equations (9)) and algebraic rearrangement of the result gave the following basal area growth model.

$$\frac{dB}{dA} = A^{-1} B [\alpha_0 + \alpha_1 S - \ln(B)] \quad (10)$$

where, $\frac{dB}{dA}$ is relative rate of basal area growth or instantaneous basal area growth rate (growth at age A).
(Equation (10)) can be integrated to obtain the equation form.

$$ln(B_2) = \left(\frac{A_1}{A_2}\right) ln(B_1) + \alpha_0 \left(1 - \frac{A_1}{A_2}\right) + \alpha_1 S \left(1 - \frac{A_1}{A_2}\right) \quad (11)$$

where, A_1 = initial age; A_2 = projection age; B_1 = initial basal area; and B_2 = the predicted basal area at age A_2
[23] pointed out that the above (Equation (10)) can be modified to

$$\frac{dB}{dA} = A^{-1} B [\alpha_0 + \alpha_1 S - \alpha_2 \ln(B)] \quad (12)$$

In order to estimate future basal area, an expression consistent with the above (Equation (12)) is

$$\ln(B_2) = \left(\frac{A_1}{A_2}\right)^{\alpha_2} \ln(B_1) + \frac{\alpha_0}{\alpha_2}\left[1 - \left(\frac{A_1}{A_2}\right)^{\alpha_2}\right] + \frac{\alpha_1}{\alpha_2} S \left[1 - \left(\frac{A_1}{A_2}\right)^{\alpha_2}\right] \quad (13)$$

(Equation (11) and (13)) are keys to developing direct volume projection equations. For prediction of a future volume, (Equation (7)) can be written as follows.

$$\ln(V_2) = \beta_0 + \beta_1 S + \beta_2 A_2^{-1} + \beta_3 (ln B_2) \quad (14)$$

where V_2 is the projected volume at A_2.
For the regression analysis, the above two basal area growth models (Equation (10) and (12)) were considered. These two expressions are rearranged as follows.

$$\frac{dB}{dA} + A^{-1} B \ln(B) = [\alpha_0 A^{-1} B + \alpha_1 A^{-1} B S] \quad (15)$$

$$\frac{dB}{dA} = \alpha_0 A^{-1} B + \alpha_1 A^{-1} B S - \alpha_2 A^{-1} B \ln(B) \quad (16)$$

To estimate the best fit of the data to(Equation (15) and (16)), Akaike`s Information Criterion (AIC) was used. For calculation of basal area at different ages, the following model developed by [23] was chosen.

$$\mathrm{DBH} = \alpha e^{-\beta A^{-1}} \quad (17)$$

where, DBH was diameter at breast height in centimeters; and α and β were parameters to be estimated.

All the calculations were analyzed by SPSS 16 and Microsoft Excel 2010.

III. RESULTS

The analysis result of (Equation (17)) was shown in (Table 4).

From the above table, basal area was calculated by applying DBH and age relationship for each plantation. For example, if age 5 years were selected, DBH in 5 years will be obtained. This DBH was used to calculate basal area per tree based on (Equation (6)). Although there were ten sample plots for each plantation, all sample plots in one plantation occupied their corresponding yield equation. Basal area of each tree from specific age was multiplied by trees per hectare at that age. Initially, trees per hectare for each plantation were the same because they had the same spacings. However, each plantation had their own DBH-age equation. Therefore, basal area per hectare would be different for the same age in each plantation. For each plantation, the age in 2016 was known from growth ring measurements. Therefore, basal area of individual tree can be directly calculated from DBH measurements in each sample plot. In these calculations, (Equation (17)) was not used. Plot level basal area were calculated by summing those of individual trees. Initial and final ages were averaged in (Equation (15) and (16)) and were used in the analysis. Initial age was set at 5 years for all plots in the present study except for the 52 year old plantation. In this plantation, initial age was set at 47 years. Average basal area was calculated with a method similar to the estimation of average stand age. Basal area growth (dB/dA) was derived by subtracting initial basal area from final basal area and divided it by the number of years involved.

Table 4. The analysis result of Equation 17 for each plantation

Plantation No.	$\mathrm{DBH} = \alpha e^{-\beta A^{-1}}$		R-Square
	α	β	
1	27.79	6.50	0.93
2	16.00	3.19	0.95
3	30.54	6.36	0.86
4	27.27	5.91	0.96
5	30.00	5.67	0.96
6	30.00	6.67	0.98
7	37.44	13.52	0.94
8	34.44	7.05	0.95
9	45.02	12.04	0.95
10	38.95	5.85	0.99

DBH is diameter at breast height (cm); A is breast height age in years; α and β regression parameters.

The parameters of the volume model (Equation (7)) and those of two basal area growth rate models (Equation (15) and (16)) were shown in (Table 5 and 6) respectively. Fig. 3 showed the predicted volume against that observed. Fig. 4 presented predicted basal area growth rate against observed one from (Equation (16)).

Table 5. Estimated values of the parameters and their significance level for Equation 7

Parameter	Estimated Value	Significance Level	F-Test	R^2
β_0	1.34	*	**	0.99
β_1	0.01	*		
β_2	-6.91	*		
β_3	1.08	*		

* significant at 0.05 probability level; ** significant at 0.01 probability level; R^2 is coefficient of determination.

Table 6. Estimated values of parameters and their significance level for Equation 15 and 16

Equation	Parameter	Estimated Value	Significance Level	F-Test	R^2	AIC
15	α_0	2.390	*	**	0.99	-250.264
	α_1	0.042	*			
16	α_0	1.006	*	**	0.99	-346.394
	α_1	0.009	*			
	α_2	-0.049	*			

* significant at 0.05 probability level; ** significant at 0.01 probability level; R^2 is coefficient of determination; AIC is Akaike`s Information Criterion.

IV. DISSCUSSION

a. Model Evaluation

In (Equation (7)) as shown in (Table 5), the coefficient of determination was very high. This equation accounted for 99 percent of the variation about mean ln V. Moreover, F-test showed that the equation was highly significant at 0.01 probability level. All the parameters in the equation were also significant at 0.05 probability level. According to statistical results, we considered that volume equation from our study was reasonable to accept.

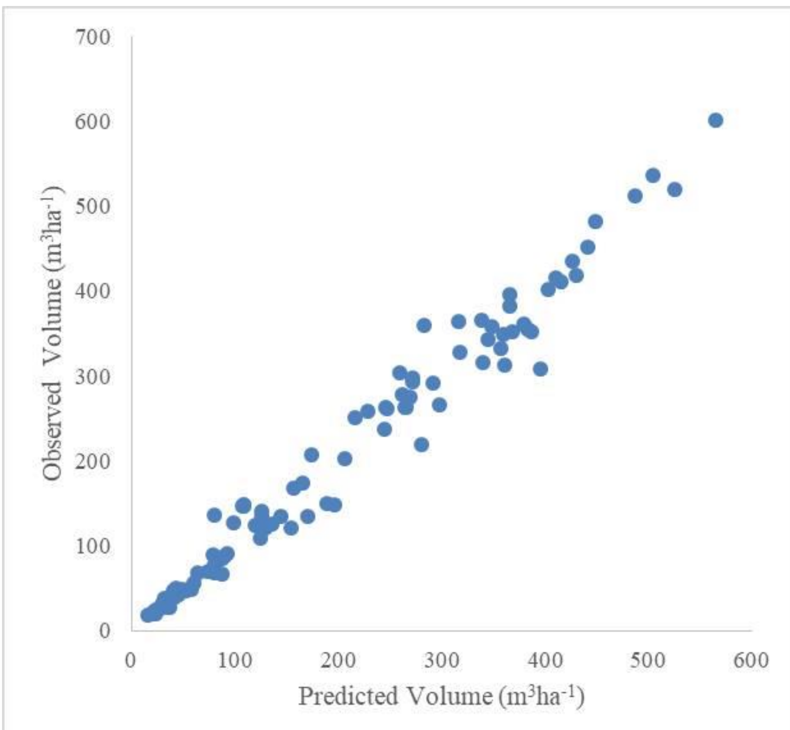


Fig.3. Predicted volume against observed volume

In (Table 6), the results from (Equation (15) and (16)) indicated that all the parameter values in two equations were significant at 0.05 probability level. F-test also showed both equations were highly significant at 0.01 probability level. The values of coefficient of determination were also very high. However, when we compared Akaike`s Information Criterion (AIC) value from (Equation (15)) with the one from (Equation (16), (Equation (16)) was better than (Equation (15)) because the value from (Equation (16)) was lower than the value from (Equation (15)). Therefore, (Equation (16)) was selected to estimate the basal area growth effectively.

b. Five Final Growth and Yield Equations from This Study

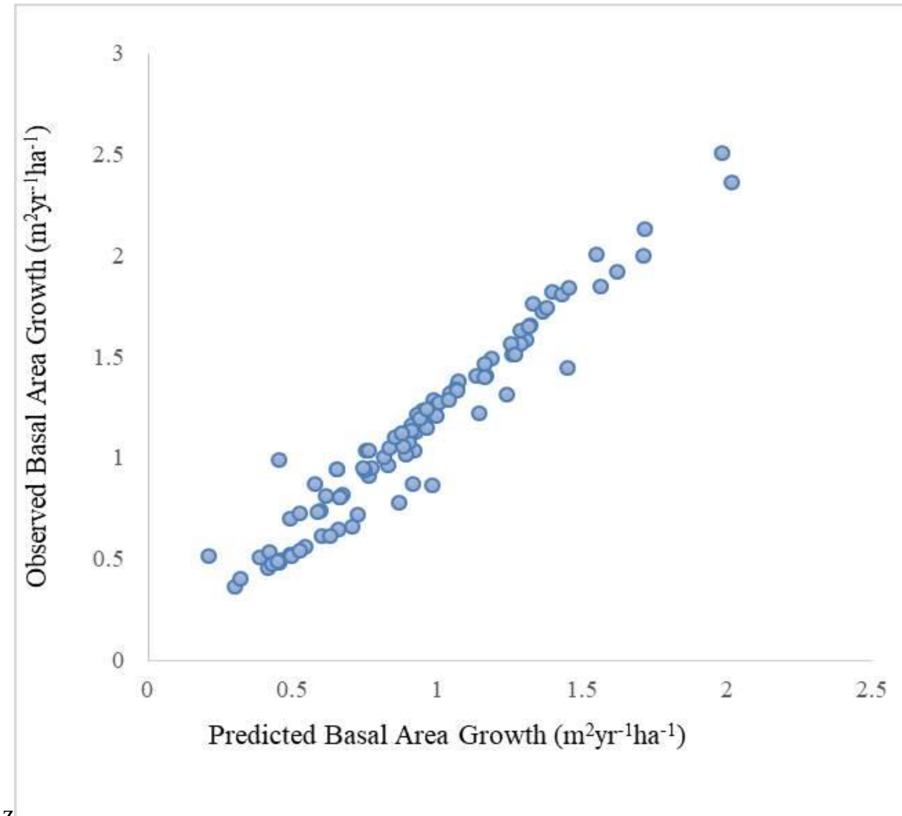
$$\ln(V) = 1.34 + 0.01\,S - 6.91\,A^{-1} + 1.08\ln(B) \quad (18)$$

$$\frac{dB}{dA} = 1.006\,A^{-1}B + 0.009\,A^{-1}BS + 0.049\,A^{-1}B\ln(B) \quad (19)$$

$$\frac{dV}{dA} = 6.91\, VA^{-2} + 1.08\, VA^{-1}(1.006 + 0.009\, S + 0.049\, lnB) \quad (20)$$

$$\ln(B_2) = \left(\frac{A_1}{A_2}\right)^{-0.049}\ln(B_1) + \frac{1.006}{-0.049}\left[1-\left(\frac{A_1}{A_2}\right)^{-0.049}\right] + \frac{0.009}{-0.049}S\left[1-\left(\frac{A_1}{A_2}\right)^{-0.049}\right] \quad (21)$$

$$\ln(V_2) = 1.34 + 0.01\, S - 6.91\, A_2^{-1} + 1.08\,(lnB_2) \quad (22)$$



z

Fig.4. Predicted basal area growth against observed basal area growth from Equation 16

[23] pointed out the following desirable logical properties for (Equation (21)).

1. As A_2 approaches A_1, ln (B_2) approaches ln (B_1). A projection model lacking this property is illogical.
2. As A_2 approaches ∞ , ln (B_2) approaches $\frac{\propto_0}{\propto_1} + \frac{\propto_1}{\propto_2} S$. Thus, the model provides an upper asymptote on future basal area and this asymptote is a function of site index.
3. Predicted future basal area values are not affected by the number of steps involved in the prediction. For example, suppose specified values of A_1, A_2, and B_1 are used to predict a future basal area B_2 and a second solution is then obtained to predict another future value B_3 from A_2, A_3, and B_2 where $A_3 > A_2 > A_1$. The predicted value obtained for B_3 will be equal to the value obtained in a single equation solution using A_1, A_3, and B_2 as inputs. Projection models that lack this property are inconsistent.

c. Comparison of the Present Study with the Old Yield Table in Myanmar

Basal area estimate from (Equation(21)) was compared with the one from the model developed by [6](Tint 1981). Data from yield table for site index 43m by him were shown in (Table 7).

Table 7. Data from yield table developed by Tint

Age (yr)	Site Index (m)	No. of Trees per ha	Mean Height(m)	Mean Diameter (cm)
15	43	920	9.8	9.5
20	43	720	11.9	12.4
25	43	510	14.2	15.7
30	43	351	16.6	19.5
35	43	195	19.8	24.7
40	43	180	21.6	27.9
45	43	158	23.5	31.3

Age (yr)	Site Index (m)	No. of Trees per ha	Mean Height(m)	Mean Diameter (cm)
50	43	140	25.4	34.7

In his study, mean volume per tree was calculated by the following equation.

$$V = (1.63)\ 10^{-5} d^{1.2577}\left(h + \frac{(h-1.3)d_1}{d}\right)\left(h - \frac{(h-1.3)d_1}{d}\right) \qquad (23)$$

where, V is mean volume in cubic meters over bark; d_1 is top diameter (if d_1 is 0, it will give the total stem volume); d is mean diameter and h is mean height.

Table 8. Comparison of basal area and some other variables

Age (yr)	Site Index (m)	Ba (m^2ha^{-1})	Bb (m^2ha^{-1})	Age (yr)	Bc (m^2ha^{-1})
15	43	6.5	6.50	15	15.59
20	43	8.7	10.01	-	-
25	43	9.9	14.06	-	-
30	43	10.4	18.61	-	-
35	43	9.3	23.62	33	27.86
40	43	11	29.09	-	-
45	43	12.1	35.00	46	53.04
50	43	13.2	41.33	52	65.96

Ba is basal area from yield table developed by Tint [13], Bb is basal area from future basal area equation (Eq.21) developed in this study) [initial age, A_1=15, and initial basal area B_1=6.5] and Bc is actual basal area from sample plots of this study.

Volume per hectare was derived by multiplying the volume per tree by total number of trees per hectare. Volume resulted from (Equation (23)) was compared with the one from (Equation (18)). Comparison was shown in (Table 8).

Table 8. Comparison of basal area and some other variables

Age (yr)	Site Index (m)	Ba (m^2ha^{-1})	Bb (m^2ha^{-1})	Age (yr)	Bc (m^2ha^{-1})
15	43	6.5	6.50	15	15.59
20	43	8.7	10.01	-	-
25	43	9.9	14.06	-	-
30	43	10.4	18.61	-	-
35	43	9.3	23.62	33	27.86
40	43	11	29.09	-	-
45	43	12.1	35.00	46	53.04
50	43	13.2	41.33	52	65.96

Ba is basal area from yield table developed by Tint [13], Bb is basal area from future basal area equation (Eq.21) developed in this study) [initial age, A_1=15, and initial basal area B_1=6.5] and Bc is actual basal area from sample plots of this study.

According to the basal area comparisons, we estimated the basal area by applying (Equation (2)). Initial age and basal area were defined as 15 years and 6.5 m^2ha^{-1} respectively. And then we projected to age 20, 25, 30, 35, 40, 45,and 50. Comparison showed that [6] yield table is underestimated in basal area. For example, in age 50, basal area from our result was approximately three times higher than that from his yield table. Actual basal area from sample plots showed that in 15 years, basal area was 15.59 m^2ha^{-1}. The results were reported in (Table 9).

Table 9. Comparison of mean stem volume and some other variables

Age (yr)	Site Index (m)	Va (m^3ha^{-1})	Vb (m^3ha^{-1})	Age (yr)	Vc (m^3ha^{-1})

15	43	4.100	32.59	15	39.31
20	43	19.10	58.35	22	127.70
25	43	35.60	90.25	-	-
30	43	51.30	127.95	-	-
35	43	60.30	171.18	33	134.31
40	43	79.90	219.79	40	262.68
45	43	98.30	273.63	-	-
50	43	117.9	332.59	52	354.80

Va is volume over bark up to approximate 10 centimeters top diameter excluding stump from volume equation developed by Tint [13]; Vb is volume over bark up to approximate 10 centimeters top diameter excluding stump from volume equation (Eq.18) developed in this study; and Vc is actual volume over bark up to approximate 10 centimeters top diameter excluding stump from sample plots of this study.

Volume from yield table for site index 43 m developed by [6] was also compared with the one from (Equation (18)) by using basal area Bb from (Table 8). The result was shown in (Table 9).

Again, the table for estimation of stand volume developed by [6] showed results which were similar to that of basal area comparisons. The empirical value of stand volume for 15 years in this study was 39.3 m^3ha^{-1}. The volume from Tint`s yield table was 4.1 m^3ha^{-1} only. This highlighted that the estimates for volume from this study was probably closer to the true value than the one from his yield table. Differences between these estimates for basal area and stand volume, and those from [6] may be due to the different modelling approaches. And also, spacing and thinning effects will influence the data collected for modelling and the final results. Moreover, Tint developed the volume equation, mean height and mean diameter by collecting the data from sample plots in the whole country and not within a specific region. Volume and basal area estimations from this study were based on data from the specific region and were site-specific. Therefore, our growth and yield prediction models will be more suitable for the current study area.

d. Comparison of Yield for Teak with Those from Other Countries

When yield estimate from this study compared with yield table for northwestern Costa Rica developed by[24] , teak will grow to 18.2 $m^2ha^{-1}$of basal area and 133.2 $m^3\ ha^{-1}$ of volume at the age of 25 years in the best site of Costa Rica. Teak in the best site of the present study area showed 122.6 m^3ha^{-1} of stem volume for the basal area of 18.2 m^2ha^{-1} for the same age. In provisional yield table for teak plantations in northern Ghana developed by [25] , they reported that for the best site, teak will reach 104.1 m^2ha^{-1} of basal area and 566.9 m^3ha^{-1} of volume. In the present study, for the best site, a teak stand will have 896 m^3ha^{-1} of volume with 104.1 $m^2ha^{-1}$of basal area. In a yield table for teak plantations in northeastern Thailand reported by [26], in the best site, teak will grow to 32.6 m^2ha^{-1} of basal area and 409.6 m^3ha^{-1} of stem volume. In our study, for the best site, teak will grow to 255.59 m^3ha^{-1} of volume when basal area is 32.63 m^2ha^{-1}. This may be due to the differences in the selection of the stem volume models, site index and its base age, although comparisons were for the same species. Thus, we can say that different modelling approaches will lead to different results which should support models to express individual situation to specific sites.

e. Comparison of Growth for Teak with Those of Other Tree Species

Mean annual basal area growths $m^2yr^{-1}ha^{-1}$ for the study plots reported by [10](Clutter 1963) for loblolly pine and by [27] for yellow-poplar stands were 0.58 $m^2yr^{-1}ha^{-1}$ and 0.55 $m^2yr^{-1}ha^{-1}$ respectively. Mean annual basal area growth for the present study for teak stand was 0.98 $m^2yr^{-1}ha^{-1}$. This showed that mean annual basal area growth for teak was greater than those of loblolly pine and yellow-poplar.

Also, the equations presented in this paper are first approximation to the growth and yield response surfaces for thinned teak stands in specific area of Myanmar. The fit of the yield equation and that of the predicted basal area growth to data compares favorably with those reported for loblolly pine by [11]. Moreover, we can expect that precision of the growth and yield predictors should be improved by establishing permanent sample plots in the studied teak plantations. Until additional data become available, however, the equations presented here are useful in estimating the effects of varying initial densities on basal area growth ($m^2yr^{-1}ha^{-1}$), stem volume growth ($m^3yr^{-1}\ ha^{-1}$), and stand production (m^3ha^{-1}).

V. CONCLUSIONS

Growth and yield models developed in this work seem to be the best tools for the management of teak plantations in the study area. Moreover, these models can be used for effective long-term management planning and decision making by any desired combination of initial density, site index, thinning regime and rotation age. Else, volume and basal area growth models can also be applied in yield regulation models because most of yield regulation formulae are based on the growth or increment. For example, in Austrian's Formula for regulation of yield, the result from volume growth is an essential input for the calculation of annual sustained yield. And also, forest managers can construct growth and yield tables based on the resultant growth and yield equations for the routine teak plantation management. Finally, the growth and yield models developed in this study are site-specific and can be used effectively to predict current volume, future volume, future basal area, instantaneous volume growth rate and instantaneous basal area growth rate for Taungoo District, Bago Region of Myanmar.

ACKNOWLEDGEMENTS

The authors acknowledge officials from the Taungoo District Forest Department and the Ministry of Natural Resources and Environmental Conservation, Myanmar, for their indispensable assistance during data collection.

REFERENCES

[1] [1]Pérez LD. Kanninen M. 2003. Heartwood, Sapwood and Bark Content, and Wood Dry Density of Young and Mature Teak (Tectona grandis Linn.F) Trees Grown in Costa Rica. Silva Fennica 37(1):45–54

[2] [2]IUFRO. 2017. The Global Teak Study: Analysis, Evaluation, and Future Potential of Teak Resources, International Union of Forest Research Organizations (IUFRO).

[3] [3]Forest Department. 2011. Forestry in Myanmar, Forest Department, Ministry of Environmental Conservation and Forestry, Myanmar

[4] [4]Avery TE, Burkhart HE. 1994. Forest Measurements, Fourth Edition, McGraw-Hill,Inc, Tokyo.

[5] [5]Naing YM. 2014 Evaluation of Site Quality and Construction of Standard Volume Table (A Case Study in Three Different Aged Teak Plantations in Bago Township, Bago Region, Myanmar), M.Sc Thesis, Kasetsart University, Bangkok, Thailand.

[6] [6]Tint K .1981. Dynamic Growth and Yield Models for Burma Teak, Ph.D Dissertation, University of Georgia Libraries

[7] [7]Mackinney AL, Schumacher FX, Chaiken LE. 1937. Construction of Yield Tables for Nonnormal Loblolly Pine Stands. J. Agric. Res. 54:531–545.

[8] [8]Mackinney AL, Chaiken LE. 1939. Volume, yield, and growth of loblolly pine in the mid-Atlantic coastal region. US For. Serv., Appalachian For. Exp. Stn. Tech. Note 33. 30 p.

[9] [9]Schumacher FX. 1939. A New Growth Curve and Its Application to Timber-yield Studies. J Forest 37:819-820.

[10] [10]Clutter JL. 1963. Compatible Growth and Yield Models for Loblolly Pine. Forest Sci 9:354-371.

[11] [11]Sullivan AD, Clutter JL. 1972. A Simultaneous Growth and Yield Model for Loblolly Pine. For. Sci. 18(1):76–86.

[12] [12]Buckman RE. 1972. Growth and Yield of Red Pine in Minnesota. US For. Serv. Tech. Bull. 1272.

[13] [13]Burkhart HE, Parker RC, Strub MR, Oderwald RG. 1972. Yields of Old-field Loblolly Pine Plantations. VPI&SU FWS-3-72.

[14] [14]Burkhart HE, Cloeren DC, Amatieis RL. 1985. Yield Relationships in Unthinned Loblolly Pine Plantations on Cutover, Site-prepared Lands. South. J. Appl. For. 9(2):84 –91.

[15] [15]Amaties RL, Burkhart HE, Burk TE. 1986. A Ratio Approach to Predicting Merchantable Yields of Unthinned Loblolly Pine Plantations. For. Sci. 32(2):287–296.

[16] [16]Ledbetter JR, Sullivan AD, Matney TG. 1986. Yield Tables for Cutover Site-prepared Loblolly Pine Plantations in the Gulf Coastal Plain. Mississippi Agric. and For. Exp. Sta. Tech. Bull. 135.

[17] [17]Borders BE, Harrison WM, Adams DE, Bailey RL, Pienaar LV. 1990. Yield Prediction and Growth Projection for Site-prepared Loblolly Pine Plantations in the Carolinas, Georgia, Florida, and Alabama. University of Georgia School of Forest Resources PMRC Res. Pap. 1990-2, Univ. of Georgia, Athens, GA.

[18] [18]Harrison WM, Borders BE. 1996. Yield Prediction and Growth Projection for Site-prepared Loblolly Pine Plantations in the Carolinas, Georgia, Alabama and Florida. University of Georgia School of Forest Resources PMRC Res. Pap. 1996-1, Univ. of Georgia, Athens, GA.

[19] [19]Ochi N, Cao QV. 2003. A Comparison of Compatible and Annual Growth Models. For. Sci. 49(2):285–290.

[20] [20]Borders BE, Harrison WM, Zhang FY, Shiver BD, Clutter JL, Cieszewski, Daniels RF. 2004. Growth and Yield Models for Second Rotation Loblolly Pine Plantations in the Piedmont/Upper Coastal Plain and Lower Coastal Plain of the Southeastern U.S. University of Georgia School of Forest Resources PMRC Res. Pap., Univ. of Georgia, Athens, GA.

[21] [21]Pienaar LV, Harrison WM. 1989. Simultaneous Growth and Yield Prediction Equations for Pinus elliottii Planations in Zululand. S. Afr. For. J. 149:48–53.

[22] [22]S.W. Martin, R.L. Bailey, and E. Jokela. 1999. "Growth and yield predictions for lower coastal plain slash pine plantations fertilized at mid-rotation" Southern Journal of Appalachian, vol. 23, no. 1, pp. 39-45

[23] [23]Clutter JL, James CF, Leon VP, Robert LB. 1983. Timber Management: A Quantitative Approach. John Wiley & Sons, United States of America.

[24] [24]Bermejo I, Canellas I, Miguel A.S. 2003. Growth and Yield Models for Teak Plantations in Costa Rica, Forest Ecology and Management, 189 (2004) 97-110

[25] [25]Nunifu TK, Murchison HG. 1998. Provisional Yield Models of Teak (Tectona Grandis Linn F.) Plantations in Northern Ghana, Forest Ecology and Management 120 (1999) 171-178

[26] [26]V. Tosporn, I. Satoshi, N. Iwao, H. Woraphun, K. Viroj, and K. Dusit, .2011. "Yield table for teak plantation in the northeast of Thailand", Royal Forest Department (RFD) , Japan International Research Center for Agricultural Sciences (JIRCAS), RFD-JIRCAS Joint Research Project, pp. 63

[27] [27]Beck DE, Della-Bianca L.1972. Growth and Yield of Thinned Yellow- Poplar, USDA Forest Service, Reserch Paper, SE 101

AUTHORS

First Author – Yan Myo Naing, Ph.D Student, Laboratory of Forest Utilization, Graduate School of Agriculture, Kyoto University, Kitashirakawa Oiwake-cho, Sakyo-ku, Kyoto 606-8502, Japan